

ScanSAR and PRECISION PROCESSOR IMPLEMENTATION AT THE ALASKA SAR FACILITY

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ABSTRACT

This paper summarizes the algorithm and hardware selection phases of the ScanSAR Processor (SSP) and Precision Processor (PP) implementation task for the Alaska SAR Facility (ASF). The SSP is being designed to specifically process RADARSAT ScanSAR mode SAR data while the PP is being designed to produce high precision image products from continuous mode SAR data from RADARSAT as well as ERS-1,2 and JERS-1. This paper describes the algorithms selected for the SSP and the PP; and reports on the hardware selection process in arriving at the target computing platform for these processors.

INTRODUCTION

The Alaska SAR Facility (ASF) situated at the University of Alaska Fairbanks (UAF) is currently undergoing an upgrade development effort to accommodate the upcoming ERS-2 (April 1995) and RADARSAT (September 1995) satellites. Although the existing hardware based Alaska SAR Processor (ASP) at ASF can easily be modified to handle the ERS-2 as well as RADARSAT continuous mode SAR data, its custom-built hardware pipeline design cannot be effectively changed to accommodate the RADARSAT ScanSAR mode data nor to satisfy the high precision processing requirements. A major part of the ASF upgrade effort therefore is to introduce a new ScanSAR Processor (SSP) to specifically handle ScanSAR mode data from RADARSAT, and a Precision Processor (PP) to provide high precision processing capability. To maintain maximum flexibility for adapting to future sensors, both the ScanSAR and precision processing capabilities are being implemented in software running on commercially available off-the-shelf computing equipment. The current plan calls for implementing the selected ScanSAR and precision processing algorithm on the same processing hardware. Based on the scope of the processing requirement, a computer market survey was first conducted to determine the applicability of the most recent and up-to-date machine configuration and architecture. Benchmark programs were developed to run on some of the more promising machines available. Finally, the performance of each candidate machine was evaluated against a set of criteria in arriving at a target platform for the SSP and PP.

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ScanSAR PROCESSOR ALGORITHM

RADARSAT ScanSAR mode data characteristics are shown in Table 1. ScanSAR utilizes multiple beams operating in a sequential fashion to provide wide swath coverage. On a per beam basis however, ScanSAR can be viewed as a SAR operating in burst mode much like that for the Magellan Venus mapping mission (1989 - 1993). The heritage of the Magellan SAR processors [1] are being fully exploited in the design of the SSP for ASF. The throughput requirement for the SSP is processing 34 minutes of RADARSAT ScanSAR data over a 16-hour day. In addition to the product specifications outlined in Table II, ASF mandates that the SAR processors be implemented under UNIX that are POSIX and X/OPEN compliant using high level programming languages such as ANSI FORTRAN and C.

Table I. RADARSAT ScanSAR Characteristics

Carrier Frequency:	5.3 GHz (C-band)
Polarization:	HH
Chirp Type:	linear FM down chirp
Chirp Bandwidth	11.583 MHz
Raw Data Sample Type:	4I/4Q
I/Q Channel Imbalance:	0.25 dB (Amplitude), 3° (Phase)
PRF's:	1270 Hz to 1390 Hz
Data Rate:	105 Mbps (direct downlink rate), 85 Mbps (on-board recorder)

NOTE: Detailed description of the downlink data can be found in reference [4].

The ScanSAR processing algorithm adopted [2,3] is briefly described below.

RANGE COMPRESSION

Range compression in the SSP is accomplished with the popular fast FFT correlation method. Effects of Doppler shift anti range walk are dealt with here by properly modifying the range reference function. Due to the large range walk variation from near to far range, range walk compensation function is updated frequently (approximately every 2048 range samples) to maintain azimuth resolution and sidelobe specification. The range compression process takes on the form:

$$S_1(m,n) = FFT^{-1}\{W_{rg}(k) \cdot e^{j2\pi RW(n)k\Delta f} \cdot FFT\{S(m,n)\} \cdot (C_0 \cdot FFT\{R(m)\})\}$$

where m denotes range sample index, n denotes range line index, $S(m,n)$ denotes input data samples within a

Table II. SSP Image Product Specification

Pixel format, bits	8
Pixel spacing, m ²	50x 50, 100 x 100, or 400x 400
Range resolution, m	75, 150, or 600
Azimuth resolution, m	75, 150, or 600
Peak side-lobe ratio, dB	<-20
Integrated side-lobe ratio (2-D), dB	<-13
Azimuth ambiguity ratio, dB	<-22
Radiometric accuracy:	
relative error, dB	+/- 0.5
absolute error, dB	+/- 2.0
Geometric Accuracy!	
absolute location error, m	< 500
Scale error, ‰	< 0.2
Skew error, %	< 0.2
Orientation error, degree	< 0.2
Beam-to-beam registration error, pixel	< 1/8

NOTES:

- a All product geocoded, with or without terrain correction, and presented in either UTM (Universal Transverse Mercator), L (Lambert), or PS (Polar Stereographic) projection.
- b Subject to accuracy of state vectors.

burst, $S_1(m, n)$ denotes range compressed data samples, k is the range frequency index, and $*$ is the complex conjugate operator. $W_{rg}(k)$ is a normalized Kaiser weighting function selected to meet range side-lobe specification. $RW(n)$ is the range walk in the n^{th} range line. C_0 is the FFT normalization factor and Δf is the frequency sampling interval. $R(m)$ is a composite function of the range pulse and Doppler shift.

AZIMUTH COMPRESSION

As noted earlier that ScanSAR data, on a per beam basis, looks exactly like data taken in burst mode. Therefore, the proven deramp-FFT [1] algorithm is selected to effect azimuth compression in the SSP. The phase histories of targets within a burst period can be modeled by linear FM (ramp) functions. Taking advantage of this behavior, the deramp-FFT technique uniquely resolves each target with an FFT after a fixed frequency ramp is removed from the range compressed and corner-turned data. The deramp-FFT azimuth compression process can be represented by:

$$S_2(m, l) = C_1 \cdot \text{FFT} \{ \text{Shift}(S_1(m, n) R_{drmp}(n), N_p/2, N_{afft}) \}$$

where m and l are the range sample and azimuth frequency indices. S_1 again represents the range compressed data samples and S_2 is the range-Doppler image pixels. C_1 is a scale factor given by $1/PRF$. The variable N_p is the number of range lines in the beam, and N_{afft} denotes the azimuth FFT length. $\text{Shift}(A(m, n), n_0, N)$ represents a left circular shift operation along the n -axis by n_0 samples on array $A(m, N)$, which is extended from $A(m, n)$ by appropriately padding it with zeros. R_{drmp} is the Deramp reference function given by

$$R_{drmp}(n) = W_{az}(n) e^{-j\pi f_r(m) ((n - N_p/2) \Delta t)^2}$$

where $W_{az}(n)$ is a normalized Kaiser weighting function selected to meet azimuth side-lobe specification. Δt is the azimuth sampling time given by $1/PRF$. The variable f_r is the Doppler frequency rate.

RADIOMETRIC COMPENSATION

Before start of processing, each input raw data sample is adjusted by the proper AGC gain factor. After processing, the resulting range-Doppler image pixel values are adjusted for effects of antenna pattern, slant range modulation, transmitter power, and receiver gain. In the case of the antenna pattern effect, a 2-dimensional array representing the compensation pattern for each beam is derived taking into account the elevation and azimuth angles of each image pixel. Details of the ScanSAR radiometric compensation and calibration processes can be found in reference [7]. The feasibility of maintaining unity gain at each processing stage is being studied in hope of minimize over- and under-flow situations.

GEOMETRIC RECTIFICATION

Before range-Doppler image pixels from various beams can be overlaid to form the final image frame, each pixel is first projected onto a common coordinate grid, e.g. along track-cross track. Since each beam covers an area of around 5 km in azimuth and 80 to 150 km in range, it is subdivided into a number of smaller blocks in order to assure the accuracy of the projection. The projection within each block is effected by two cascaded 1-dimensional resampling processes using a second order polynomial. The range-Doppler image is first converted to range-along track domain, followed by a second conversion into the cross track-along track domain. Both conversions are implemented using four-point interpolators. A detailed discussion of this process can be found in reference [3] and [5].

MULTI-LOOK OVERLAY

After pixels from each beam are laid onto a common along track-cross track grid, corresponding pixels from different beams are then combined through an averaging process to achieve a higher number of looks for speckle noise reduction. To satisfy a desire to maintain a constant number of looks over the entire image frame, some of the pixels in each beam may have to be discarded when the specified number of looks has already been attained.

CO-ORDINATE TRANSFORMATION

This final step converts the resulting along track-cross track multi-look image into user specified Polar Stereographic (PS), Universal Transverse Mercator (UTM), or Lambert (L.) projection. The co-ordination transformation steps are similar to the geometric rectification process referenced above.

PRECISION PROCESSOR ALGORITHM

The purpose of the Precision Processor is to provide an alternate and improved processing capability for

processing continuous mode SAR data at ASF. Its goal is to capitalize on up-to-date processing techniques and algorithms to achieve high processing efficiency and image fidelity. It also represents an initial step in achieving a longer term goal of replacing the hardware based ASP which is the current processing workhorse at ASF. The ASP was designed and built in the eighties and is becoming relatively costly to operate and to maintain.

The stated requirements for the Precision Processor are similar to those for the ScanSAR Processor with the exception of resolution and the addition of a phase accuracy specification. The PP handles RADARSAT single beam data taken in standard, fine resolution amongst other modes, and its resolution requirements are in the 10 m to 50 m range. A phase accuracy requirement is also introduced for the standard beam product of not more than 3 degrees. To meet this phase accuracy requirement, the more modem chirp scaling class of algorithm [6,8,10] is being considered for the PP. The theory and expected performance of this algorithm is well publicized in literature that includes [8,9,10]. Implementation details of the chirp scaling algorithm for PP will be discussed at a later date.

HARDWARE SELECTION

The hardware selection process for the ASF SSP and PP took 6 months and 2 peer reviews to complete. This process involved the following steps:

- 1 initial scoping of class of machine,
- 2 performing computer market survey and identifying candidate platforms,
- 3 developing representative benchmark software and selection criteria,
- 4 performing benchmarking and platform evaluation,
- 5 selecting the target platform.

SCOPING OF TARGET MACHINE SIZE

With the requirements understood and algorithms specified, rough counts of the number of operations required to produce typical image products were compiled by totaling all necessary computational operations in each steps of the algorithm. This included FFT's in the range and azimuth compression processes, and resampling in the projection and co-ordinate transformation processes to name a few. Based on the throughput requirement, an initial estimate of the target class of machine was determined to be around 500 million floating point operations per second (500 MFLOPS) sustained.

COMPUTER MARKET SURVEY

A computer market survey was then conducted to seek out suitable candidate hardware platforms. The criteria for inclusion in the evaluation process were mainly the projected computational capability and the timely availability of a suitably configured platform to support our benchmarking effort over the period of March and September of 1994. Estimated system cost was not an initial criterion noting that some of the more expensive super computers may be available under a time used reimbursement lease arrangement to UAF. Machines

identified in this effort represented both the Symmetric Multi-Processor (SMP) and the Massively Parallel Processor (MPP) classes of system architecture. SMP machines included the Power Challenge series of models from Silicon Graphics, Inc. (SGI) and the DEC-7000 series models from Digital Equipment Corp. (DEC). MPP representatives were the CRAY T3D model, the Intel Paragon model, the Thinking Machine Corp.'s CM-5 model, and the IBM S1'-2 model.

The hardware characteristics and configurations of the candidate platforms are listed in Table III.

BENCHMARK SOFTWARE

With a larger processing emphasis placed on. ScanSAR, the benchmark software covered all major computational and data I/O steps in the ScanSAR algorithm. The benchmark code was adapted from development code written in FORTRAN and C, and made to mn on a SUN workstation model 670 using a single processor. It ingested raw data samples in 8I /8Q format from disk, performed the necessary data unpacking, performed the ScanSAR data processing steps outlined in the previous subsections, repacked the output pixels and output to disk. The input and output files as well as timing results obtained on the SUN were kept as a reference for comparison.

Overall, the benchmark software consisted of the following categories of software modules:

- 1 Computation module performing -
 - a) FFT's used in range compression and azimuth compression,
 - b) vectorized computation with indexed memory access for interpolation and resampling,
 - c) vectorized computation with direct memory access for multi-look overlay.
- 2 Data movement module performing -
 - a) data packing & unpacking,
 - b) corner turn,
 - c) framelet truncation in geometric rectification process.

TABLE 111. Candidate Platform Characteristics

MACHINE:	MAX. # of PROC. BENCH. MARKED	PEAK RATED MFLOPS PER PROC.	CLOCK RATE (MHz)	MEMORY ¹ SIZE (MBytes)	SECOND. ARY CACHE MEMORY MBytes	OPERAT- ING SYSTEM	PRO. GRAM- MING LANGU- AGE
MPP MACHINE:							
IBM SP2 (RS fore)	32	268	67	128	N / A	AIX	F77,C
CRAY T-3D (DEC ALPHA)	128	150	150	32	N/A	UNICOS	F77,C
CM-5 (TI cm ⁵)	32	128	32	32	N / A	CMOST	F90,F77,C
PARAGON (INTEL i860XP)	332	100	50	32	N / A	C% F/I	F77,C
SMP MACHINE:							
SGI P-Challenge (MIPS R8000)	18	300	75	204s	4	IRIX	F77,C
DEC-7000 (DEC ALPHA)	6	273	27s	2048	4	OSF/1	F77,C

NOTE: 1 Memory used for benchmarking, size represents per processor for the MPP machine and machine total for SMP machine.

- 3 Data 1/0 module performing -
 - a disk read/write,
 - b message passing between processors in MPP machines.

All software modules are written in ANSI FORTRAN or C language comprising typically less than 100 lines of code each. Some pertinent parameters of the benchmark software are listed below:

Number of Range Samples Per Beam	8192
Number of Azimuth Samples Per Beam	65
Range FFT Length	2048
Azimuth FFT Length	64
No. image Framelet Samples Along-track	-60
No. Image Framelet Samples Cross-track	1250
No. Final Image Samples Along-track	5000
No. Final Image Samples Cross-track	5000

BENCHMARK AND PLATFORM EVALUATION

The benchmark software was first ported to each individual platform and in all cases made initially to run on only a single processor unit of the candidate platform. The resulting timing and output files were collected and checked against the reference obtained on the SUN 670. The ported code on each candidate machine is then **parallelized** using standard vendor supplied routines and procedures. Although consultation from vendors on specific issues was solicited, the actual code porting and optimization on all machines were performed by our hardware selection team so that a subjective measurement of code development effort and code portability can be maintained.

A prioritized list of machine attributes was also developed to assure the thoroughness of the evaluation and to maximize the objectivity of the platform selection process. A total of 10 specific attributes were included. Listed in descending order of importance to the ASF SSP and PP applications, they were:

- 1 throughput capability
- 2 software porting and development effort
- 3 operating system and compiler maturity
- 4 expected system reliability and maintainability
- 5 purchase cost
- 6 adaptability to precision processing algorithm
- 7 system expandability
- 8 compliance with Portable Operating System & Interface guide (POSIX)
- 9 availability and support of the Open Software Foundation (OSF) Distributed Computing Environment (DCE)
- 10 availability of appropriate digital signal processing (DSP) library routines

BENCHMARK RESULTS HIGHLIGHT

A summary of the results and observations derived from the benchmark experience is given below:

- 1 The size of available cache memory can substantially influence the performance of a processing unit as

evident in timing results from the CRAY T3D and the DEC-7000, both of which uses the Alpha processing chip. While the rated per processor MFI.OPSRate of the CRAY T3D is less than 2 times slower than that of the DEC-7000, benchmark timing indicates that the CRAY is more than 3 times slower mainly due to the absence of secondary cache memory on the CRAY processors.

- 2 Handling of data packing and unpacking is important to overall performance. In the case of the Thinking Machine CM-5, this is found to be a major shortcoming. Also, it is observed that CM-5's handling of FFT's with length less than 128 is particularly inefficient. To approach rated performance, CM-5 requires data records be sized to multiples of 1K long, which can be impractical for ScanSAR mode processing. The CM-5 model is unique amongst the candidate machines in supporting programming in FORTRAN 90 in addition to FORTRAN 77.
- 3 There are two approaches in effecting parallelization of the ScanSAR processing algorithm. The first one is so called 'fine grain' approach whereby each data burst is broken down into range lines with each line assigned to a different processing unit for range processing. The resulting data is then corner-turned. This is then followed by assigning each individual azimuth line to a different processing unit for azimuth processing. This is in contrast with the 'coarse grain' approach whereby a complete data burst is assigned to a particular processor for range processing, followed by corner-turn, and azimuth processing. It is observed that the 'coarse grain' approach is especially more efficient than the 'fine grain' counterpart in the SMP architecture. This is due primarily to better utilization of the cache memory and therefore reduced demand on memory 1/0 bandwidth in the 'coarse grain' approach (see Figure 1).
- 4 Also evident from Figure 1 is the fact that processing efficiency of the SMP machines trails off rapidly as the number of processing units increases. This is caused by the fact that in the SMP architecture where all processing units share a common memory, memory bus contention eventually creates a bottleneck that throttles the overall performance of the machine. In the examples shown in Figure 1, the sample MPP machine is able to remain well above 90% efficient with as many as 16 processing units. Its efficiency tends to degrade linearly and gradually as more processing units are added. In contrast, the best of the sample SMP machines shown in Figure 1 achieves no better than 90% efficiency when the number of processing units reaches 12; moreover, its efficiency degrades rapidly thereafter.

TARGET PLATFORM DESCRIPTION

Based on our evaluation of the candidate platforms against the list of prioritized attributes, the target platform selected is the IBM SP-2. For the specific ASF SSP and PP applications, it is determined that two IBM SP-2 units

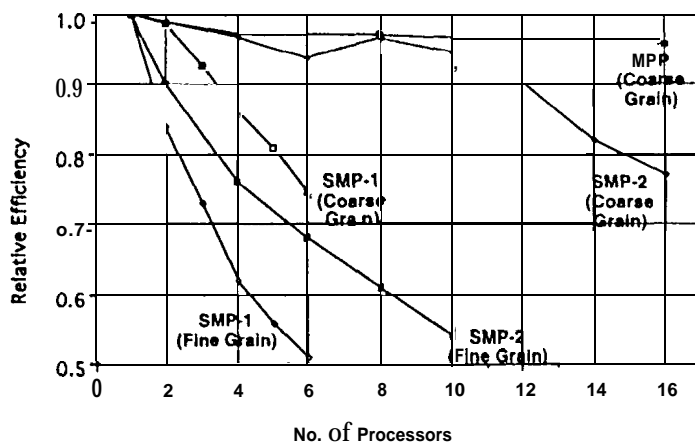


Figure 1. Computational Efficiency

with 8 nodes each will provide the needed performance and reliability. It is expected that each unit will handle processing of 17 minutes of RADARSAT ScanSAR data and perform precision processing on another 2.5 minutes of continuous mode data in a 16-hour day.

The hardware configuration of a single 8-node SP-2 unit is illustrated in Figure 2.

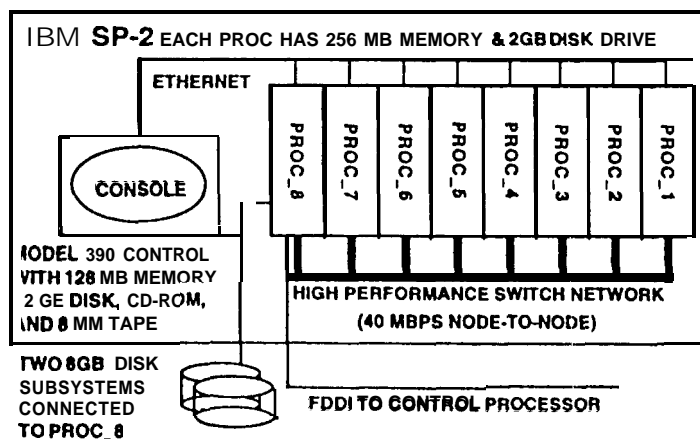


Figure 2. Target Platform Configuration

CURRENT STATUS

The ScanSAR and Precision Processor development effort is currently progressing on track to provide operational capabilities at ASF by March and October of 1996 respectively. The ScanSAR processing algorithm has been prototype on a 4-processor SGI Challenge machine which will also be used to process limited amount of RADARSAT ScanSAR data in support of RADARSAT

satellite commissioning activities scheduled within a few weeks of the RADARSAT launch in September 1995. In the meantime, the code running on the SGI is being ported and adapted to run on an 8-node IBM SP-2 platform which will be one of two machines supporting the operational ScanSAR processing function at ASF. The precision processing algorithm is still in the process of being finalized. Current emphasis is on completing the prototyping of the algorithm, and obtaining some early performance predictions. More information regarding the SSP and PP will be presented as the development work progresses.

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